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13. ABSTRACT (*Maximum 200 words*)

Germanium- silicon epitaxial heterostructures have been grown and evaluated for possible use in far- infrared detectors. Growth was performed by ultra- high vacuum chemical vapor deposition at temperatures of 550- 600 °C. Multiple quantum well structures were grown and evaluated by X- ray diffraction, secondary ion mass spectrometry, and photoluminescence. Infrared absorption measurements showed that free- carrier absorption was dominant for normal- incidence illumination. Heterojunction internal photoemission structures have also been grown and characterized. The results show that both structures can be successfully fabricated using this technique when growth parameters are correctly chosen.

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Development of Germanium- Silicon Growth Technology

Final Report
AFOSR Contract F49620-92-J-0155

February 1, 1992- January 31, 1995

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Research Objectives

We report here our work on the growth of detector structures for long- wavelength infrared focal plane arrays (IRFPAs). Such arrays are of interest for both civilian and military imaging applications in the 3- 5 µm and 8- 12 µm atmospheric transmission windows. Depending upon the wavelength range and operating temperature, readout circuitry consists of either MOSFET arrays or CCD arrays with peripheral circuits. The major requirements for detectors in such displays are

(1) Achievement of background- limited infrared photodetector (BLIP) performance with 300 K background illumination,
(2) response to normally- incident radiation,
(3) compatibility with silicon readout circuitry, and
(4) excellent pixel- to- pixel response uniformity.

Good performance can be obtained today in the 3- 5 µm region using the PtSi- pSi Schottky barrier detector. Present technology does not, however, offer a completely satisfactory solution for imaging in the 8- 12 µm region. The cutoff wavelength of IrSi- pSi Schottky barrier detectors is not completely optimal and other problems include a difficult and nonreproducible process technology. HgCdTe offers very high quantum efficiencies (greater than unity due to photoconductive gain) but uniformity of the material remains problematic. Much research has focused on GaAs/ AlGaAs quantum well photodetectors, but most designs (those using the conduction band offset) are not sensitive to normally incident radiation, requiring additional processing to form grooves or gratings on the surface. Further, neither HgCdTe nor GaAs can be grown epitaxially on silicon with good quality. While detectors can be fabricated separately and bonded to the silicon substrates, this approach is expensive and also there are increasing difficulties with thermal expansion mismatch when large arrays are fabricated.

Here, also, recent research has focused on the use of silicon heteroepitaxy to fabricate potentially useful structures. These include quantum well infrared photodetectors (QWIPs), the heterojunction internal photoemission (HIP) detector, and other devices such as silicide/ GeSi Schottky barrier detectors. In this report we summarize our AFOSR- funded work on photodetectors during the February 1992- January 1995 time period. We also place that work into context by briefly discussing the activities of other groups and our own work prior to that period.

Research Progress

Our work on Ge_xSi_{1-x}/Si heterostructures began with an equipment grant (AFOSR-89-0144) which funded construction of an ultra- high vacuum chemical vapor deposition (UHV/ CVD) growth system. This was one of the first attempts to develop capabilities similar to those reported by B.S. Meyerson [1]. As the published equipment and process descriptions were incomplete, this involved substantial uncertainty. Even so, our system was the first of this type to be successful. AFOSR funding for research on infrared detectors was subsequently obtained (F49620-92-J-0155 and F49620-93-1-0387). Some of the related work discussed below was funded by NSF, Westinghouse R&D Center, and the Caltech President's Fund.

A. UHV/ CVD System and Capabilities

UHV/ CVD is a growth technique in which deposition takes place from gaseous reactants at low temperatures (500- 600 °C) and pressures ($\approx 10^{-3}$ Torr). A schematic diagram of the Carnegie Mellon system is shown in Fig. 1. A detailed description of this system was published in [2]. The system is capable of UHV base pressures (p_{O_2}, $p_{H_2O} < 10^{-10}$ Torr). The reactants used are hydrides- silane, germane and diborane and phosphine for doping. Operation at low temperatures and pressures has the effect of suppressing gas phase reactions leading to uniform deposition even when multiple wafers are closely stacked together. A further advantage of low pressure is the short residence time which facilitates the abrupt transitions necessary in heterojunction devices.

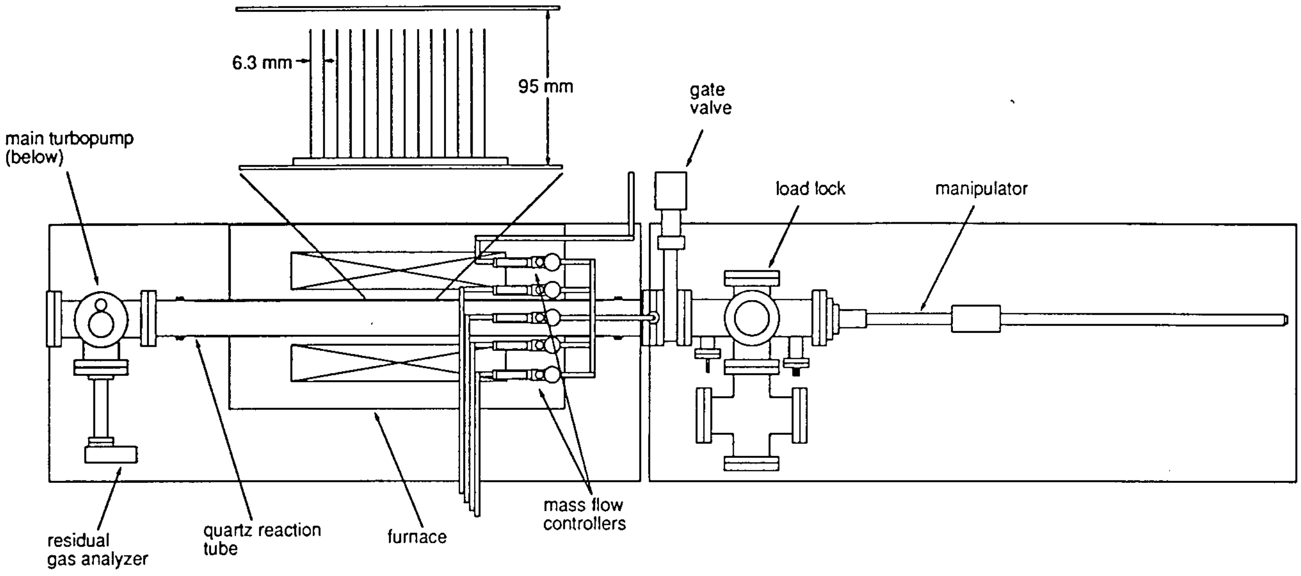

Figure 1. The Carnegie Mellon UHV/ CVD system.

In our early work with UHV/ CVD, we concentrated on developing a basic understanding of the growth process. We published the first measurements of Ge_xSi_{1-x} growth rates by UHV/ CVD over a range of temperatures [3]. The nonmonotonic dependence of growth rate on germane flow was later explained by Robbins et al. [4] using composition- dependent sticking coefficients. We used published studies of the surface reactions of silane [5] and hydrogen [6] to develop a simple model for the kinetics of silicon growth [7]. In this model, the growth rate is determined by competition between the chemisorption of silane and the desorption of hydrogen from surface monohydrides. Later, we showed that the same model explained growth rates in a number of other techniques [8]. In the same paper [7], we measured the dependence of growth rate and doping concentration on phosphine flow. A model was proposed which explained the observed growth rate suppression. In a subsequent study of boron doping [9], we extracted the diborane sticking coefficient and demonstrated silicon doping concentrations up to 10^{20} cm^{-3}. We also conducted a systematic study of thermal and other cleaning approaches [10], showing that oxide desorption was limited by kinetics at temperatures below $\approx$ 750°C in systems with sufficiently low p_{H_2O}. We demonstrated selective growth by UHV/ CVD and explored its limits [11]. The uniformity of layers grown by UHV/ CVD was quantified by X- ray diffraction measurements and compared with Monte Carlo simulations [12,13,14]. Our understanding of the UHV/ CVD technique and its limitations was summarized in a review paper [15]. Our later, more comprehensive review paper contrasted the various CVD techniques available for Ge_xSi_{1-x} heterostructure growth [16]. Common aspects were brought out and the current state of research on quantum well and bipolar junction devices was summarized.

With an understanding of the basic physics and chemistry of the growth process, we proceeded to apply UHV/ CVD to the growth of structures for silicon- based infrared detectors.

Our work was the first attempt to use CVD to grow aggressive detector structures which had been initially developed using MBE. While in some ways CVD techniques give results superior to MBE growth under similar circumstances, CVD growth frequently requires additional process development. This is because growth rates and impurity incorporation rates can depend in a complex fashion on growth conditions. The payoff for this process development work is a growth process which is more suitable for manufacturing.

B. Research on Multiple Quantum Wells for Infrared Detectors

Figure 2 shows the band diagram of a multiple- quantum well infrared photodetector. This type of detector was first demonstrated in GaAs/ AlGaAs by Levine et al. [17]. Infrared detection can be obtained using various different transitions as indicated in the figure. Transitions between the quantum ground and an excited state in the well can be followed by tunneling out of the well. Alternatively, a transition can be made directly to an extended state.

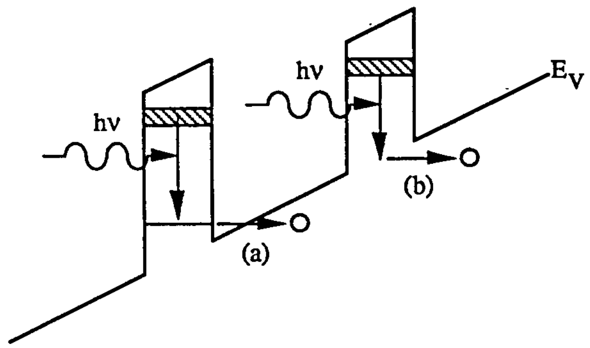

Fig. 2. Band diagram of multiple- quantum well infrared photodetector. Illustrated are (a) a transition to an excited state followed by tunneling and b) a transition to an extended state.

When we began our work in 1992, first reports of Ge_xSi_{1-x}/ Si quantum well detectors had just been published [18]. These structures were grown by MBE and did not exhibit the desired normal- incidence response. Successful growth of *undoped* quantum wells by CVD was just being reported [19]. Dramatically different photoluminescence spectra were reported for different growth techniques [19,20]. There was considerable excitement, however, due to reports of electroluminescence in $Ge_{0.18}Si_{0.82}$ thick layers [21] and multiple quantum wells [22].

As our primary objective was the growth of infrared detectors, at the outset we grew doped multiple quantum wells. Initially we used the modulation doping approach of Eglash et al. [23]. We characterized these structures by high resolution X- ray diffraction [24] and photoluminescence [14]. Typical X- ray diffraction measurements are shown in Fig. 3, illustrating multiple satellite peaks and excellent uniformity across a 75 mm wafer. Photoluminescence measurements showed the no- phonon (NP) exciton recombination lines and replicas previously reported by Sturm in CVD material [19]. We observed the expected quantum shift with well width [25] although the peaks were appreciably broader than reported for undoped quantum wells. Our papers were the first reports of the growth of *doped* multiple quantum wells by a CVD technique.

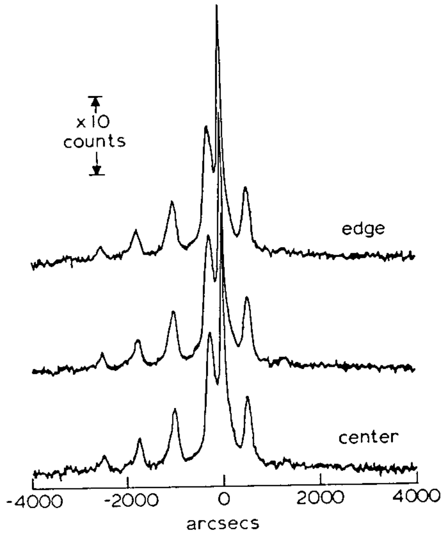

Figure 3. High- resolution X- ray diffraction spectra for $Ge_{0.24}Si_{0.76}$/ Si multiple quantum wells (25 Å wells, 175 Å barrier) grown by UHV/ CVD.

In order to explore the cause of the broader lines, we subsequently grew a series of undoped multiple quantum wells [26]. Typical photoluminesence measurements are shown in Fig. 4 illustrating NP line widths (≈ 3- 4 meV) very comparable to the best results obtained by other groups. In the same paper, we observed electroluminescence similar to that reported by other CVD growers [27,28]. Our work thus contributed to a growing body of work showing that luminescence was qualitatively different in CVD and MBE- grown material. We were also able to show a transition from quantum well luminescence to dislocation band luminescence at an effective stress of 150 MPa. In contrast, MBE material shows quantum well luminescence alone only below 50 MPa, and only a broad peak at ≈ $E_{G(GeSi)}$-120 meV for effective stresses greater than 110 MPa. The "broad peak" is thought to be associated with platelet formation in MBE material [29]; evidently platelet formation does not occur during UHV/ CVD growth.

Note that these photoluminescence measurements were performed on as- grown (unannealed) samples. Our investigations of undoped multiple quantum wells thus demonstrated that UHV/ CVD material was comparable to, or in some ways better than, MBE- grown material. We thus proceeded to fabricate a range of doped multiple quantum well structures suitable for normal- incidence infrared detectors. We focused on strained- layer structures grown on (100) silicon substrates, that is, utilizing holes confined in Ge_xSi_{1-x} by the valence band offset.

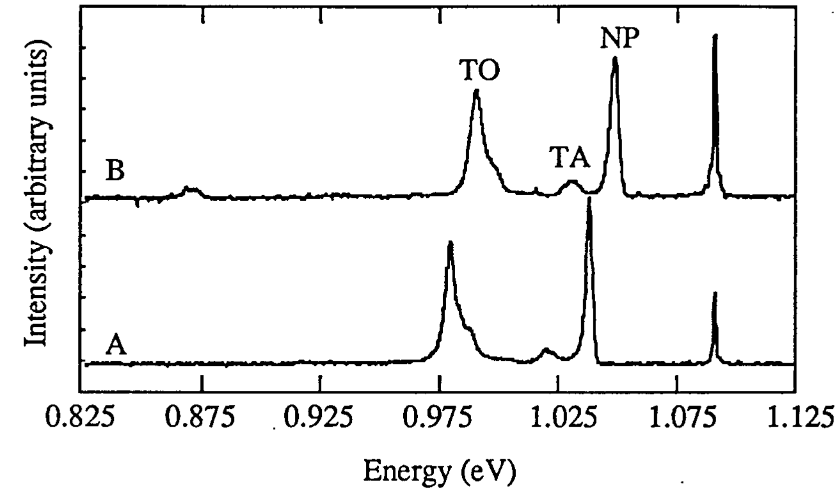

Fig. 4. Measured photoluminesence spectra at 4.2 K for UHV/ CVD- grown undoped multiple quantum wells (150 Å barriers). Sample A: 20 X 57 Å $Ge_{0.19}Si_{0.81}$ wells; sample B: 20 X 45 Å $Ge_{0.19}Si_{0.81}$ wells. The line at 1.093 eV is the boron TO replica from the substrate.

At the time we grew our first structures of this type the experimental picture was rather confusing. Park et al. had reported a normal incidence detector with peak response at about 7 µm utilizing the free- carrier absorption process [30]. In this detector, holes gain momentum parallel to the surface followed by a scattering event which results in emission over the barrier. This process was of course known in Schottky- barrier detectors such as PtSi and the HIP detector, and can be designated a HH0 $\rightarrow$ HH0(excited) transition. Subsequently the same group reported strong normal- incidence absorption via intervalence- subband transitions [31]. In this case the transitions were in the 3.6 - 5 µm region for well compositions in the range x = 0.60 to 0.30. It was noted that the absorption was strong only for large x where the coupling between conduction and valence bands is strong. (An unfortunate consequence of this is that these transitions are expected to become weak when the germanium fraction is decreased to shift the transition into the desired 8- 12 µm region). Finally, People et al. [32] reported both HH0 $\rightarrow$ HH1 and HH0 $\rightarrow$ SO0 intervalence subband transitions (normal incidence) in $Ge_{0.25}Si_{0.75}$ quantum wells. They were able to measure detector response in the 8- 11 µm region. In contrast, Wang and coworkers observed a strong HH0 $\rightarrow$ HH1 transition only when a component of the electric field was normal to the surface [33], and reported large normal- incidence absorption only when $x > 0.30$ [34].

In order to clarify this situation, we began a program of growth and characterization of a wide range of quantum well structures, with emphasis on those with predicted threshold wavelengths in the 8- 12 µm region. (That is, we did not reproduce the structures grown by Park et al. with x » 0.30 which had transitions in the 3.6- 5 µm region). Normal- incidence, single-pass FTIR measurements were performed in order to observe transitions most interesting for detectors. In addition, characterization by photoluminescence, X- ray diffraction, SIMS and TEM was performed to confirm structural parameters and also to assess material quality.

Three classes of devices were examined:

1. Thin barrier devices
   20 wells 26- 58 Å thick, $x = 0.19$
   doped in well to $\approx 2 \times 10^{19}$ - 4×10^{19} cm^{-3}
   barrier thickness $\approx$ 140 Å
   doped cap and contact layers

2. Thick barrier devices
   10 wells 33- 62 Å thick, $x = 0.24$- 0.32
   doped in well to $\approx 4 \times 10^{18}$ - 4×10^{19} cm^{-3}
   barrier thickness $\approx$ 300 Å
   doped cap and contact layers

3. Multiple quantum wells (no doped contact layers)
   10 wells 30- 53 Å thick, $x = 0.24$- 0.32
   doped in well to $\approx 4 \times 10^{18}$ - 4×10^{19} cm^{-3}
   barrier thickness $\approx$ 300 Å
   undoped cap and contact layers

Only devices of type 2 have barrier regions thick enough to realize low dark currents and also have doped contact regions. Thus only these are suitable for detector characterization.

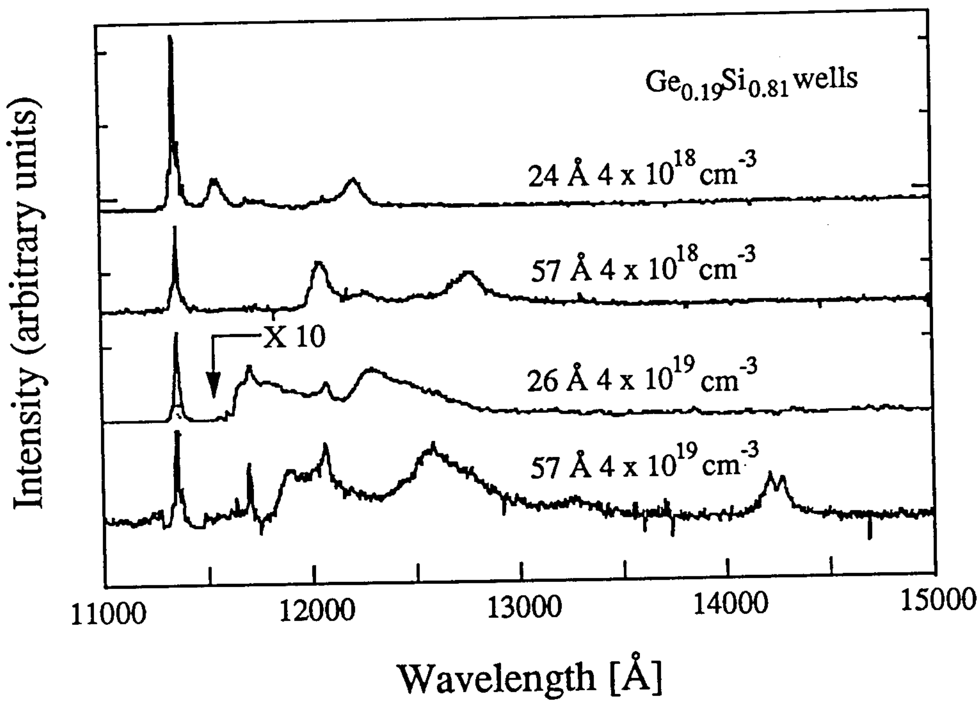

Fig. 5. Measured photoluminescence spectra of multiple quantum well samples with doped barrier regions. The barrier thicknesses were approximately 150 Å.

We discuss first characterization of type 1 (thin barrier) devices. Figure 5 shows measured photoluminesence spectra for samples with two different doping concentrations. The exciton recombination luminescence is still visible although broadened and much reduced in intensity compared to undoped samples. The observation of photoluminesence indicates that nonradiative recombination is fairly weak and therefore that the material is of high quality. The positions of the NP lines and their shift with well width are in good agreement with those calculated using a one-dimensional effective mass model.

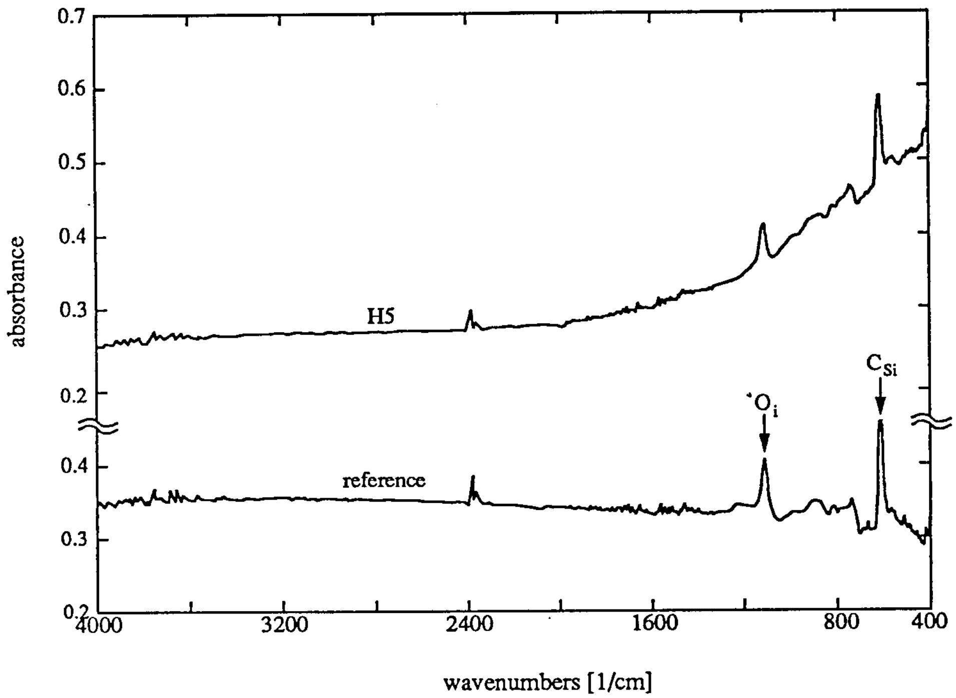

Fig. 6. Normal incidence FTIR measurements on type 1 sample. The $Ge_{0.19}Si_{0.81}$ well was 58 Å thick with the center boron- doped to 4 x 10^{19} cm^{-3} (raw data). The reference sample shows oxygen interstitial and carbon substitutional absorption peaks attributable to the silicon substrate.

Normal incidence FTIR measurements on type 1 samples showed only a monotonically increasing free carrier component as shown in Fig. 6. When we reported these results, we attributed the absence of intersubband transitions to an inappropriate choice of sample parameters [35]. Indeed, in some of these samples the heavy doping pushed the predicted positions of the intersubband transitions to very long wavelengths. This was consistent with our observation of very low device resistance at 77 K. In type 2 and 3 samples, we addressed these problems by (1) increasing the barrier thickness to reduce leakage current, and (2) increasing the germanium fraction and examining a wider range of samples in an effort to bring the intersubband peak within the range of interest. Extensive characterization was also carried out in order to guarantee the quality of the layers examined.

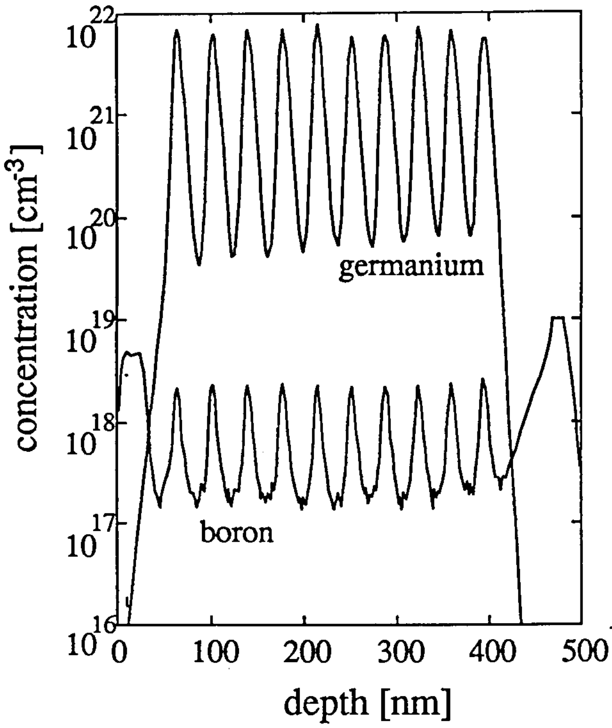

Figure 7. SIMS profile of quantum well sample: 10 X 55 Å $Ge_{0.28}Si_{0.72}$ wells doped 4×10^{18} cm^{-3}; 300 Å barrier regions; with undoped cap and buffer.

We consider first the results of structural characterization. Figure 7 shows the results of SIMS measurements on a sample of type 3 (no doped contact layers). The profile shows that the boron is located within the well regions and shows excellent abrupt transitions for both boron and germanium. The leading edge transition slopes are about 3 nm/ decade which compares very favorably with MBE samples grown at the same temperature (5- 11 nm/ decade) [36]. Figure 8 shows a TEM cross section of the same sample, again showing excellent abruptness and confirming the planarity of interfaces.

A wide variety of type 2 and 3 samples were grown and characterized by normal- incidence FTIR. The samples investigated included some which were specifically grown to be nearly identical to those of People et al. [32]. As we were seeking transitions in the 8- 12 µm range, we did not reproduce the high- x samples of Karunasiri et al. [33], although several of the samples grown had similar doping concentrations. A total of 21 different growths were studied.

Typical FTIR results are shown in Fig. 9. Samples with doped contact layers (type 2) exhibited one or two peaks in absorption in the 3- 4 µm region superimposed on a monotonically increasing absorption due to free carriers. Type 3 samples showed only free- carrier absorption. We have conclusively identified the peaked absorption as an interference effect arising from reflections arising from the doped lower contact region. Evidence for this includes (1) the absence of the peak in samples without a doped contact layer; (2) absence of correlation with predicted shifts with well composition and thickness; and (3) a shift toward shorter wavelengths after

etching part of the epitaxial layer. Note that the position of peak we observe is similar to that reported by Park et al. However, the absorption mechanism they propose is expected to be weak for small x, which is consistent with the absence of this absorption process in our samples.

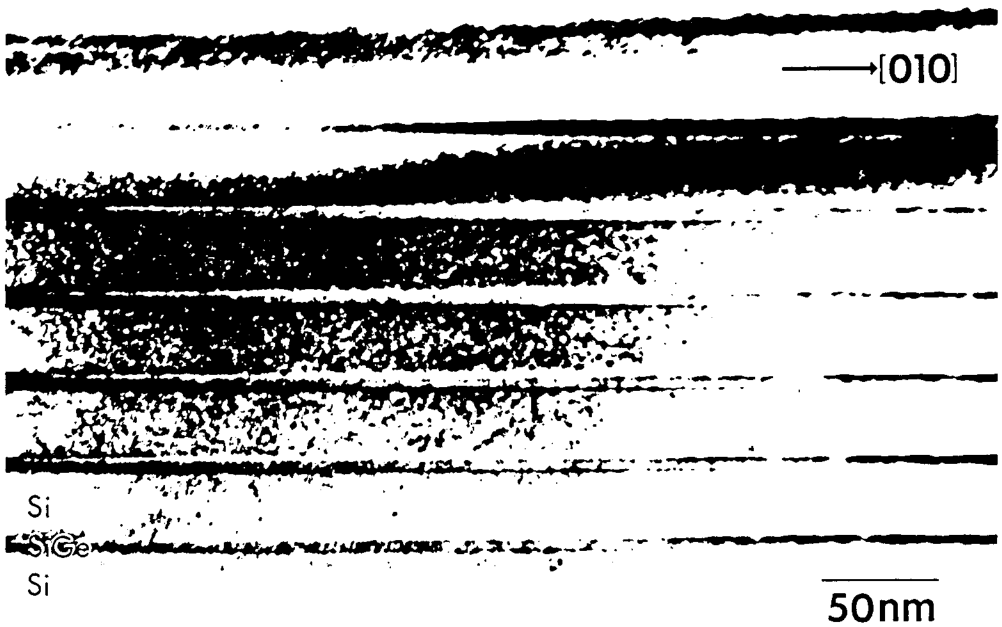

Fig. 8. TEM photograph of quantum well sample: 10 X 55 Å $Ge_{0.28}Si_{0.72}$ wells doped 4×10^{18} cm^{-3}; 300 Å barrier regions; with undoped cap and buffer.

In Fig. 9, the lower spectrum is for a sample with similar dimensions to the one reported by People et al. [32] except for an order of magnitude larger well doping. The dotted curve shows the expected absorption when the measurements of People et al. are scaled according to the relative doping. We can conclusively rule out the existence of a similar absorption peak in our samples.

These results show that inter- subband transitions either do not occur in normal incidence in the wavelength range of interest or they are substantially weaker than the free- carrier absorption process. As the free- carrier absorption process has been demonstrated to be useful for detectors, these results suggest that future work should be directed at utilizing this absorption process effectively in detectors. This is in fact the focus of our future work, as will be discussed in a subsequent section.

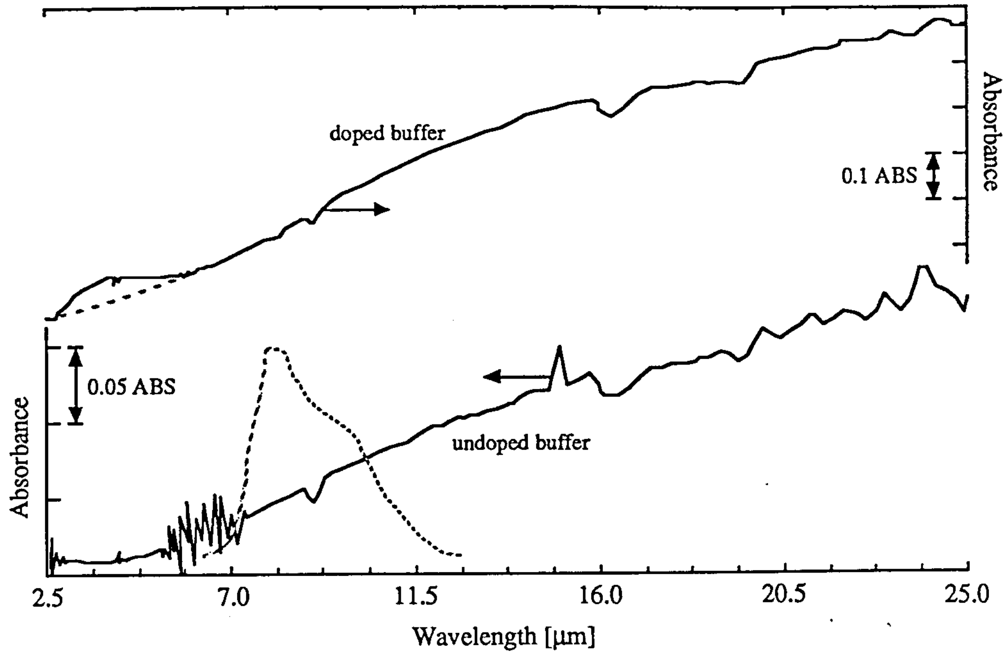

Fig. 9. Normal incidence FTIR measurements on two samples: (top) 20 X $Ge_{0.32}Si_{0.68}$ 30 Å doped 4 x 10^{18} cm^{-3}, 1000 Å silicon buffer doped 1 x 10^{20} cm^{-3}; (bottom) 20 X $Ge_{0.24}Si_{0.76}$ 44 Å doped 4 x 10^{19} cm^{-3}; undoped buffer.

Finally, we note that several quantum well samples have been fabricated into detector structures using a three- mask passivated mesa process. These samples have been forwarded to W. Mitchel at Wright Laboratory who has agreed to perform low- temperature photoconductivity measurements.

C. Research on Heterojunction Internal Photoemission Structures

The heterojunction internal photoemission (HIP) detector (Fig. 10a) was first reported by Lin and Maserjian in 1990 [37]. This was an implementation of a structure previously patented by Shepherd and coworkers [38]. Subsequently Lin and coworkers improved the quantum efficiency to 0.2% at 10 μm by increasing the boron doping to 5 x 10^{20} cm^{-3} [39]. A similar structure using a silicon buffer layer was described by Liu et al. [40], and fabrication of arrays has been reported by Tsaur et al. [41].

In the HIP detector, holes in a Ge_xSi_{1-x} absorbing region are excited into higher energy states by free- carrier absorption of infrared photons. For normally incident illumination, the carriers gain momentum parallel to the surface; however, after scattering, some have sufficient energy to surmount the barrier. The physics of the detection process is thus similar to silicide Schottky barrier detectors although in the HIP detector the threshold wavelength is tunable by changing the germanium fraction x of the absorbing region. Typically the absorbing region is doped very heavily (as much as 5 x 10^{20} cm^{-3} [39]). The thickness of the absorbing region is typically 200 Å, of the order of the hot hole scattering length.

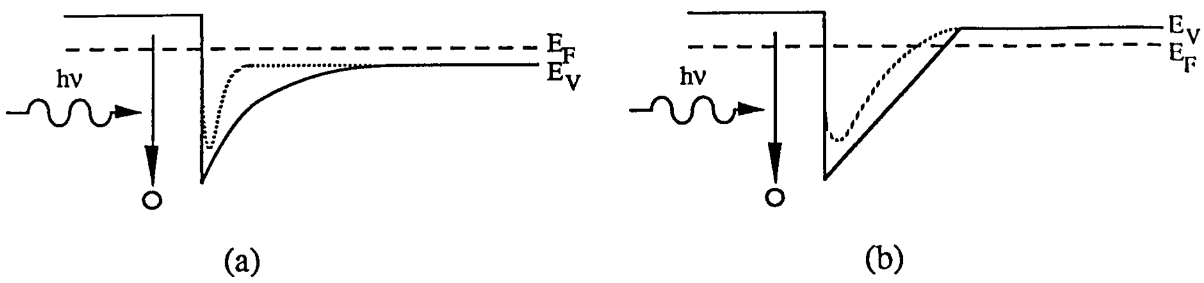

Fig. 10. HIP structures (a) absorbing layer grown directly on lightly doped substrate and (b) silicon layer grown on heavily doped substrate. Dotted lines indicate qualitatively the effect of unintended boron interfacial and bulk doping.

Growth of these structures is challenging because of the combination of relatively large x, layer thicknesses near the equilibrium critical thickness, and very high doping. Another less obvious complication is residual boron in the growth system. Consider first a HIP structure grown directly on a lightly doped substrate (Fig. 10a). A boron spike at the original growth interface (which is common in low- temperature growth by either MBE [42] or CVD [43]) causes a high field at the interface, enhanced tunneling, and an apparent decrease in the barrier height. In another structure, a silicon layer is grown first; however, residual doping in this region can have similar consequences.

We experienced difficulties with both residual bulk boron doping and interfacial boron in our initial efforts to grow HIP structures by CVD. We also encountered difficulty with the formation of thickness undulations, especially in boron- doped films. In the following, we summarize our research into approaches for controlling this problems and our recent results on HIP detectors.

We consider first the issue of thickness undulations. It has long been known that high germanium fractions and high growth temperatures lead to the onset of nonplanar growth [44]. However, recent work by Pidduck et al. [45] showed the development of sinusoidal undulations in the early stages of nonplanar growth. This elastic relaxation process is not an indication of growth defects and indeed is more likely to occur in material with few dislocations. A similar phenomena has been observed and modelled [46] in other strained- layer epitaxial materials.

Our interest arose because we observed enhanced thickness undulations in doped material. Figure 11 contrasts the morphology of undoped and doped ($N_A = 8 \times 10^{19}$ cm^{-3}) $Ge_{0.32}Si_{0.68}$ epitaxial layers grown at 600 °C. The undulations are more severe (and unacceptable for devices) in material of doping levels comparable to those required in HIP detectors. As the formation of undulations is mediated by surface diffusion, the natural choice is to attempt growth at lower temperatures. By reducing the growth temperature to 550 °C, we have obtained nearly planar, heavily doped $Ge_{0.32}Si_{0.68}$ layers [47].

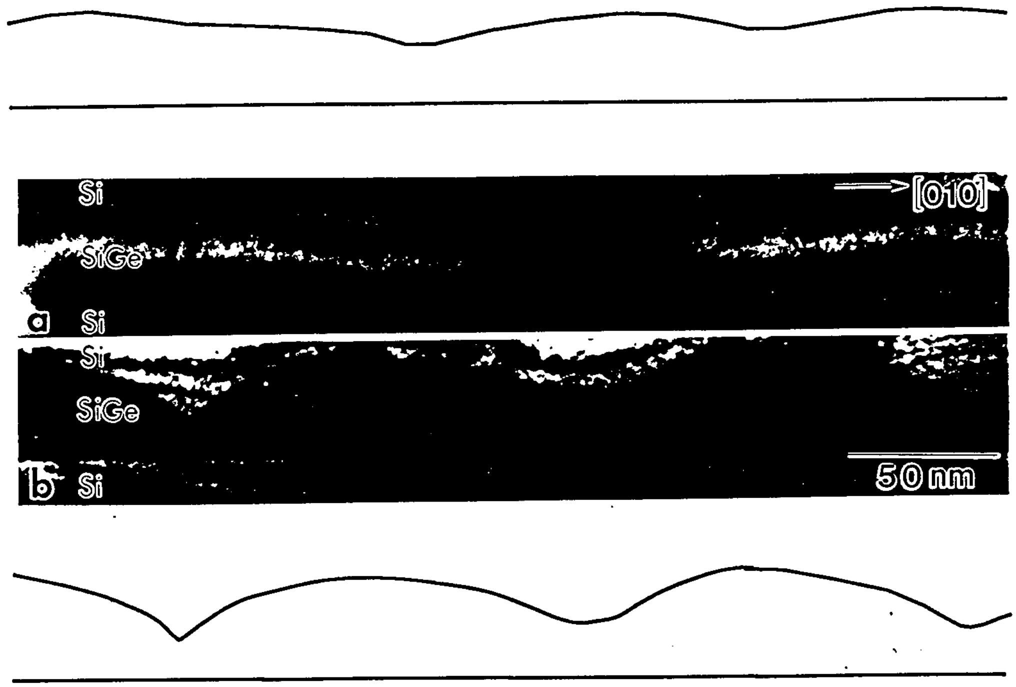

Fig. 11. Cross sectional TEM of $Ge_{0.32}Si_{0.68}$ epitaxial layers: (a) undoped and (b) doped 8 x 10^{19} cm^{-3}; grown at 600 °C. Pronounced sinusoidal undulations are a result of partial elastic relaxation. The undulation amplitude is considerably reduced when growth is at 550 °C.

Although the immediate problem has been solved, there remain fundamental questions about elastic relaxation. Current models predict undulation wavelengths about an order of magnitude greater than observed [47]. In addition, the increase in amplitude with boron concentration is contrary to theory as is the apparent absence of this effect in thin layers (quantum wells). We are continuing to investigate this effect, particularly using high resolution X- ray diffraction (in collaboration with M. Capano, Wright Laboratory).

Another important issue is residual doping with boron. Boron contamination, especially at the initial growth interface, is frequently observed in low- temperature silicon epitaxy. Based on published surface science, bulk residual doping was not expected to be a problem in UHV/ CVD. However, we have observed boron transport via the boron suboxide BO during thermal oxide desorption [47]. Introduction of a cleanup run and improved wet chemical processing has reduced both boron contamination components to acceptable values [47].

Typical results using our optimized growth process are shown in Fig. 12 and 13. Fig. 12 shows the measured photoresponse of a detector with a 150 Å $Ge_{0.32}Si_{0.68}$ active layer doped to N_A = 8 x 10^{19} cm^{-3}, using the structure of Fig. 10b. A threshold wavelength of 13.5 μm is observed. The quantum efficiency of this detector is low because of the relatively small N_A. Recent growths have been performed with projected doping up to approximately 2 x 10^{20} cm^{-3}, and these samples are now being prepared for characterization.

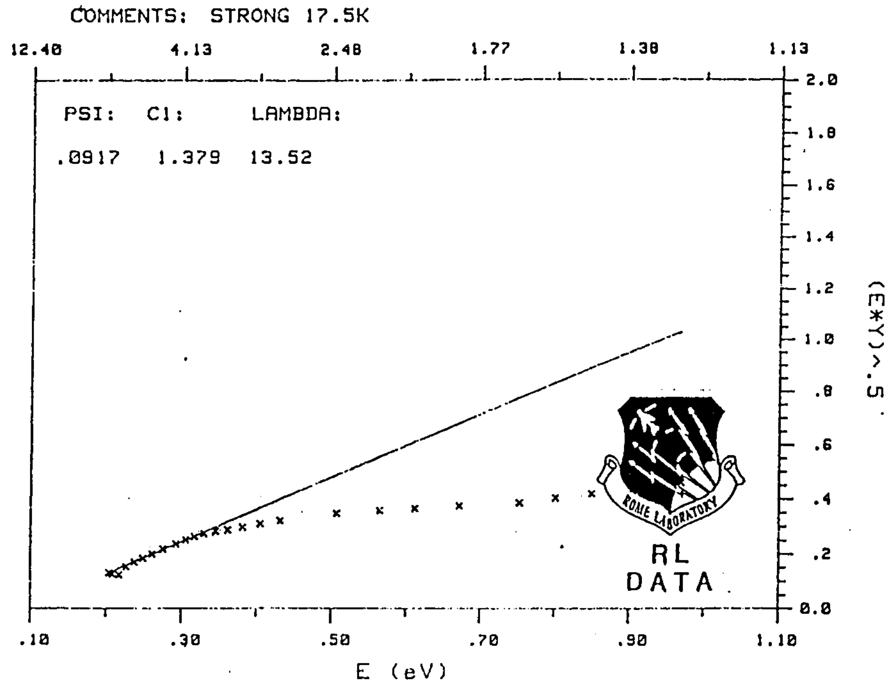

Fig. 12. Fowler plot for HIP structure with 150 Å $Ge_{0.32}Si_{0.68}$ active layer doped to $N_A = 8 \times 10^{19}$ cm^{-3}. (Data from M. Weeks, Rome Laboratory).

Process integration with readout circuitry will require growth of the Ge_xSi_{1-x} directly on the substrate as in Fig. 10a. Figure 13 shows the measured I(V) characteristics for such a structure, where the thin $Ge_{0.40}Si_{0.60}$ layer was selectively grown within a contact window in SiO_2. The characteristics are highly ideal and low leakage currents are obtained, even at bias voltages of -5 V.

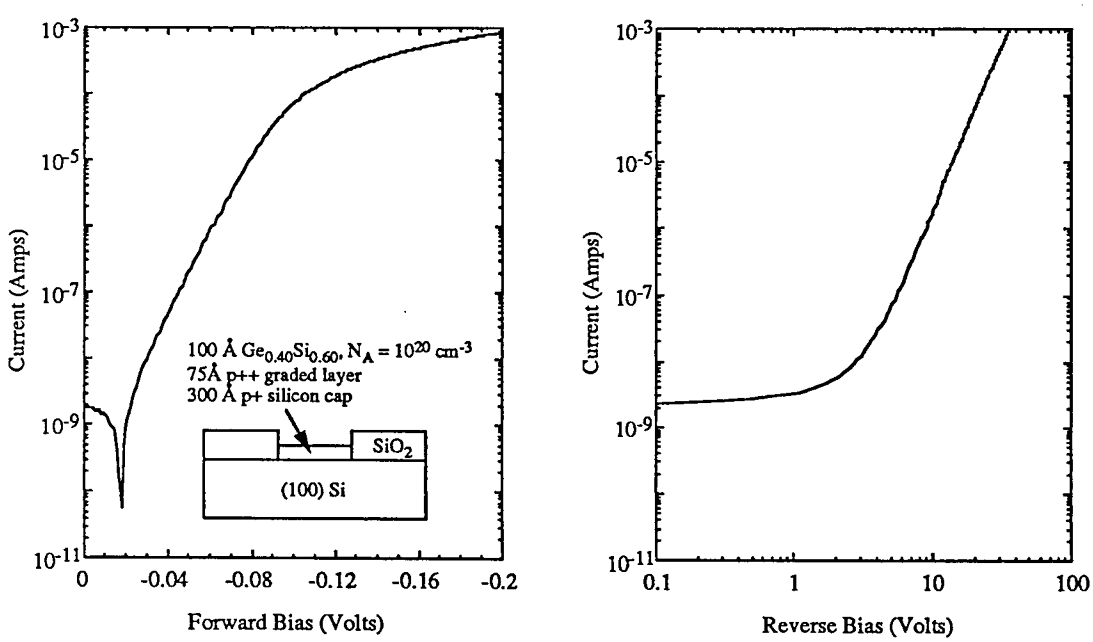

Fig. 13. Measured forward and reverse I(V) characteristics at 77K for HIP structure grown selectively in an SiO_2 window.

Finally, we have taken some steps toward integration of detectors and readout circuitry. Figure 14 shows the cross section of a combined FET/ infrared detector structure (HIPFET) which has been invented by E. Fossum of JPL. With zero gate bias, a potential well is formed by the p- δ doping which collects holes injected by the Ge_xSi_{1-x}/ Si heterojunction. A moderate positive bias (readout mode) induces a channel in the n- δ doped region where the conductance is influenced by the stored hole charge. Large negative gate voltage provides a reset mode in which stored hole charge is removed.

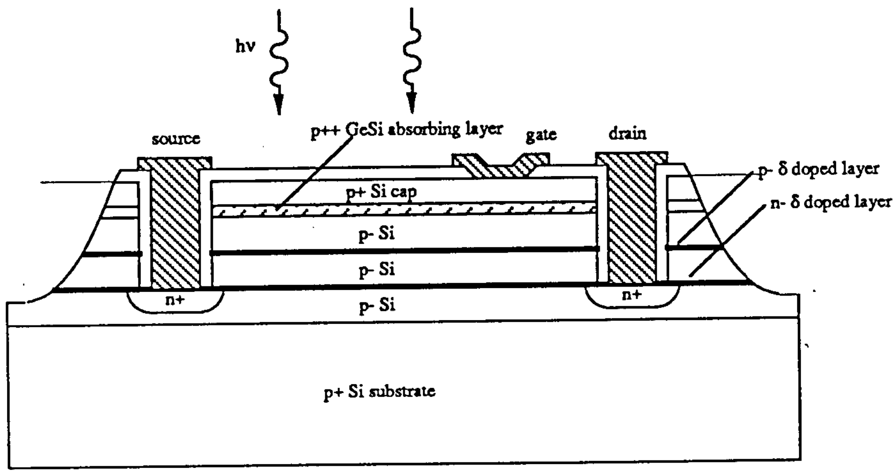

Fig. 14. HIPFET structure.

The combined FET/ detector structure has been fabricated at CMU using a process and masks designed at CMU. All epitaxial layers were grown by UHV/ CVD and a total of two epitaxial growths were required. Operation of the devices as a gate- controlled FET at 300 K has been demonstrated and IR characterization (at JPL) is planned in the near future. This work illustrates the potential of UHV/ CVD for advanced devices, and also illustrates a first step toward process integration.

[The HIPFET work was supported by the Caltech President's Fund and represents a collaboration between CMU and JPL].

Planned Future Work

A contract for the continuation of this research work has been approved by AFOSR effective February 1, 1995. While the emphasis on IR detector structures will continue, there are some additional topics which will be investigated. The following briefly describes the objectives of the continuing program.

Our research will focus on IR detector structures although some of the work may lead toward improved emitters. The proposed research has two thrusts. First, we will identify and characterize an optimal detector for the 8- 12 μm region. This will very likely *not* be a multiple quantum well detector, for reasons which follow directly from recent work by us and others. An

important part of the work will involve process integration, that is, development and demonstration of a process which is suitable for implementation in arrays. This portion will involve fabrication of small detector arrays on partially processed wafers obtained from Rome Laboratory.

Secondly, we will conduct exploratory research directed at integrable detectors for the 1.3 μm region. We will focus on a detector with a superlattice active region possibly grown on relaxed buffer layers. We will also examine the incorporation of other column IV species, most likely carbon. Work on SiGeC is at a very early stage, and it is unclear what effect carbon has on luminescent efficiency, absorption strength, and energy gap. A sustained research program, similar to the one which has led to our present understanding of Ge_xSi_{1-x}, is necessary to assess the applicability of this material in detectors and emitters.

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R. Strong, Ph.D. ECE (anticipated September, 1995)

Interactions

Conference Presentations

"Comparison of Mesa-Etched and Ion-Implanted Ge_xSi_{1-x} Heterojunction Bipolar Transistors," D.W. Greve and M. Racanelli, *1992 Spring MRS, Symposium on Defect Engineering in Semiconductor Growth, Processing, and Device Technology*, San Fransciso, CA.

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"UHV/ CVD Epitaxy of Silicon and Germanium- Silicon Heterostructures," D.W. Greve, R. Misra, R. Strong, and T.E. Schlesinger, Electronic Materials: Session on Chemical Routes to Group IV Epitaxy, 40th Symposium of the American Vacuum Society, (Orlando, FL, November, 1993).

"Heterojunction Infrared Diodes Using Ge_xSi_{1-x} Films Grown by Ultra High Vacuum Chemical Vapor Deposition," R. Strong, T.J. Knight, S.M. Vyas, D.W. Greve, and T.E. Schlesinger,

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"Growth of Epitaxial Ge_xSi_{1-x} for Infrared Dectectors by UHV/ CVD," S. Vyas, D.W. Greve, T. Knight, R. Strong, and S. Mahajan, (presented at the 4th European Vacuum Conference, Uppsala, Sweden, June, 1994).

"Growth and Characterization of Ge_xSi_{1-x} Films by Ultra High Vacuum Chemical Vapor Deposition for Infrared Detector Applications, R. Strong, T.J. Knight, D.W. Greve, and T.E. Schlesinger, (presented at the 1994 Electronic Materials Conference, Boulder, CO).

"Infrared Absorption in Ge_xSi_{1-x}/ Si Quantum Wells," R. Misra, D.W. Greve, and T.E. Schlesinger, (presented at the 1994 Electronic Materials Conference, Boulder, CO).

Other Presentations (seminars, etc.)

"Growth and Characterization of Germanium- Silicon Multiple Quantum Wells," Condensed Matter Physics Seminar, Carnegie Mellon University, March 5, 1992.

"Growth and Characterization of Multiple Quantum Well Structures Grown by UHV/ CVD," Seminar at Kodak Electronics Research Laboratory, March 16, 1992.

"Growth and Characterization of Multiple Quantum Well Structures Grown by UHV/ CVD," Informal Seminar, Bell Laboratories Murray Hill, March 19, 1992.

"Growth and Characterization of Ge_xSi_{1-x} Multiple Quantum Well Structures," Seminar at Wright Laboratory, Wright Patterson Air Force Base, October 30, 1992.

"Growth and Characterization of Ge_xSi_{1-x} Multiple Quantum Well Structures," Seminar at Department of Electrical Engineering, Notre Dame University, November 11, 1992.

"Applications of UHV/ CVD- Grown Silicon and Germanium- Silicon," Electronic Imaging Laboratory Seminar, Xerox Palo Alto Research Center, November 13, 1992.

"Surface Processes During BN Growth," D.W. Greve, AFOSR Topical Research Review, (Dayton, OH, October, 1993).

"Growth of IR Detector Structures by Multi- Wafer CVD," D.W. Greve, AFOSR Topical Research Review, (Boston, MA, November, 1993).

"UHV/ CVD Epitaxial Growth of Germanium- Silicon and Application to Infrared Detectors," Department of Electrical Engineering Seminar, University of Vermont (March 11, 1994).

"UHV/ CVD Epitaxial Growth of Germanium- Silicon and Application to Infrared Detectors," Department of Electrical Engineering Seminar, University of Delaware (April 8, 1994).

"Germanium- Silicon Infrared Detectors," Condensed Matter Physics Group Seminar, Physics Department, Carnegie Mellon Univeristy (April 14, 1994).

"UHV/ CVD Epitaxial Growth of Germanium- Silicon and Application to Infrared Detectors," Solid State Devices Seminar, Naval Research Laboratory, (May 12, 1994).

"Application of Ultra- High Vacuum Chemical Vapor Deposition to Infrared Detectors," Seminar at the National Research Council of Canada, November 4, 1994.

Other Activities

Co- chairman, Quantum Devices Session at Silicon- Based Heterostructures II, American Vacuum Society Fall Meeting, November, 1992, (Chicago, IL).

Session Chair, session on Integrated Processing for Optoelectronics, Symposium on Integrated Processing for Micro- and Opto- Electronics, European MRS, May, 1993.*

Chairman, Session at the Active Matrix Liquid Crystal Displays Symposium, (Bethlehem, PA, October, 1993).

NSF Panel for Solid State and Microstructures Program, May 24, 1994.

Inventions/ Patent Disclosures

(none)

Collaborations

Wright Laboratory, WPAFB

M.A. Capano- high resolution X- ray diffraction
W. Mitchel- spectrally resolved photoconductivity

Air Force Institute of Technology

R.L. Hengehold- cathodoluminescence and UV- excited photoluminescence

Rome Laboratory

P. Pellegrini- measurements on heterojunction internal photoemission detectors

Jet Propulsion Laboratory

E. Fossum- heterojunction internal photoemission FET (integrated detector/ readout; supported by Caltech President's fund)

Transitions

Our work has provided information about germanium- silicon growth techniques, and in particular information about the advantages and limitations of UHV/ CVD, to a wide variety of individuals and organizations. Visitors to our facilities for discussions of germanium- silicon growth include

P. Thompson, NRL
R. Hengehold, AFIT
J.-O. Fornell, EpiGress, Sweden
S. Sinharoy, Westinghouse Science& Technology Center
J. Goldman, Riber

We have also provided advice on growth system design and choice of growth technology to potential users. Examples include

P. Potyraj, Westinghouse Baltimore
L.C. Kimerling, MIT
M. Haynes, Westinghouse Science& Technology Center
T. Krumbaker, RL/ERE

Finally, we have provided access to the UHV/ CVD system for training and initial experiments to researchers from Westinghouse and Lehigh University. This has resulted in one publication ["All-silicon internal barrier detectors: a voltage-tunable LWIR staring focal plane technology," T.A. Temofonte, T.T. Braggins, P.R. Emtage, M.J. Bevan, R.N. Thomas, H.C. Nathanson, J. Halvis, R. R. Shiskowski, and T.E. Wilson, Proceedings of IEEE International Electron Devices Meeting; San Francisco, CA, USA; 13-16 Dec. 1992.